

Periodization of Plyometrics: Is There an Optimal Overload Principle?

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Abstract

Lievens, M, Bourgois, JG, and Boone, J. Periodization of plyometrics: Is there an optimal overload principle? *J Strength Cond Res* XX(X): 000–000, 2019—This study investigated the acute and chronic effects of 3 plyometric training (PT) programs with equal training loads (intensity \times volume \times frequency) on speed, agility, and jumping performance. Forty-four male recreational team sport athletes were either assigned to a program that increased training volume with exercises of mixed intensity (Mix), kept training volume equal and increased exercise intensity (LowHi), increased training volume and kept exercise intensity low (Low), or to a control group (Control). Subjects were trained twice a week for 8 weeks and were tested for 5- (5 m) and 10-m sprint (10 m), 5 \times 10-m shuttle run (5 \times 10 m), squat jump (SJ), countermovement jump without and with arm swing, and standing broad jump. Five-, 10- and 5 \times 10-m performance did not change ($p > 0.05$) after the PT program. Jumping performance, except for SJ ($p = 0.114$), improved significantly ($p < 0.05$) in the PT groups compared with the control group. However, no mutual differences ($p < 0.05$) were established between plyometric groups. In addition, it was shown that a PT of high intensity was more likely to affect performance and blood inflammation markers in the following days. To conclude, PT programs following a different overload pattern, i.e., different combination of volume and intensity, but equal training load showed similar performance effects in recreationally trained men. However, before competition, a PT of low intensity is preferred over a PT of high intensity to avoid a decline in performance.

Key Words: jumping, training, stretch-shortening cycle

Introduction

For several decades, plyometric training (PT) has been used as an essential part of sport programs (14). Plyometric training is characterized by repeated jumps or throws at relatively high intensities (22). More specifically, PT aims to enhance the properties of the stretch-shortening cycle by preceding the concentric muscle action with an eccentric lengthening of the agonistic muscle. Hereby, 3 phases can be distinguished: the eccentric prestretch phase, the coupling phase, and the concentric-shortening phase (7,9). During the eccentric prestretch, also referred to as preloading, the muscle spindle of the muscle-tendon unit, the series elastic component and the parallel elastic component are stretched. The longer the duration of the coupling phase, i.e., the time between the prestretch and the actual concentric muscle contraction, the more of the stored elastic energy will disappear as heat. It is believed that the eccentric prestretch phase will facilitate and improve the resultant muscle contraction (2,5). Therefore, PT is considered as the missing link between strength and speed training, and the benefits of adding PT to an athlete's regular training program are generally accepted (20).

Furthermore, it is shown that a PT program has, to a variable extent, positive effects on the development of jumping power, speed, agility, and even running economy (4). Results from a meta-analysis indicated that vertical jumping height increased

with on average 3.9 cm (effect size [ES]: 0.84) after PT (10). A smaller impact was found on the development of sprinting speed: performance improved with 0.007 ± 0.002 seconds (ES: 0.32), 0.06 ± 0.05 seconds (ES: 0.39), and 0.10 ± 0.07 seconds (ES: 0.29) for 10-, 20-, and 50-m sprint, respectively (29). Agility performance, measured by a T-test and Illinois agility test, was also improved through PT with, respectively, 0.89 ± 0.49 seconds (ES: 0.87) and 0.84 ± 0.61 seconds (ES: 0.99) (1).

For quite a few years now, athletes, coaches, and sport scientists have tried to determine the optimal training load to increase dynamic performance (32). Although, generally, positive impacts of PT on performance have been observed, ambiguity regarding the optimal training modalities and more specific to the principles of training progression to maximize performance still exists. On the one hand, researchers are in search of the best methodology to quantify plyometric exercise intensity, and on the other hand, training studies are looking for the optimal training protocol. Although it is well established that the training outcome depends on the total training load, i.e., volume \times intensity \times frequency, the intensity parameter is often overlooked when comparing different protocols (24). Although it is suggested that the principle of overload should be followed, current literature guidelines are often based on anecdotal guidelines rather than scientific results (9).

Besides the positive chronic effects of PT, it should be noted that the eccentric component of plyometric exercises can induce muscle fatigue in the days after training. A decrease in squat jump (SJ) and countermovement jump (CMJ) performance (8–20%) was found up to 72 hours after a single PT session consisting of 50 hurdle jumps (50 cm) and 50 drop jumps (50 cm) (6). Also, muscle damage, measured as creatine kinase (CK) and lactate dehydrogenase (LDH), and delayed onset of muscle soreness

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Journal of Strength and Conditioning Research 00(00)/1–8

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(DOMS) are often reported after PT sessions. A peak in LDH (+165%) and DOMS (+387%) was noted 24 hours after PT; CK peaked at 48 hours (+275%); and all remained elevated up to 72 hours after the session (6). Therefore, when programming PT, it is essential to have insight into both chronic and acute effects of the session, especially when planned in proximity to competition.

The main purpose of this study was to investigate the effect of 3 PT interventions with a similar training load progression (i.e., 10% weekly increase) imposed by a different combination of volume and intensity on sprinting, agility, and jumping performance. The first group increased training volume with exercises of mixed intensity (Mix); the second group kept training volume equal and increased exercise intensity (LowHi); and the third group increased training volume and kept exercise intensity low (Low). We hypothesized that performance adaptations would be quite similar across training groups because the total training load was kept equal. In addition, the acute load of the Mix, LowHi, and Low PT sessions was determined by analyzing performance and inflammation parameters before and 24 and 48 hours after the final training session.

Methods

Experimental Approach to the Problem

Chronic effects on sprinting, agility, and jumping capacity were examined after a period of 8 weeks, in which 2 PT sessions per week were performed. The training load was matched across the experimental groups and increased by approximately 10% per week (12). Subjects were either assigned to a program that increased training volume with exercises of mixed intensity (Mix), kept training volume equal and increased exercise intensity (LowHi), increased training volume and kept exercise intensity low (Low), or to a control group (Control). To examine the impact of a single bout of PT, i.e., the acute effect, performance and additional blood parameters were examined 24 and 48 hours after a PT of mixed, high, and low intensity (Figure 1).

Subjects

Forty-four physically active men (19–27 years) volunteered for this study and were randomly assigned to Mix ($n = 11$), LowHi ($n = 11$), Low ($n = 11$), or Control ($n = 11$) (Table 1). Previous experience in PT and structured lower-body strength training were assessed through a questionnaire and set as exclusion criteria for this study. The questionnaire showed that all subjects were active in team sports (soccer, basketball, or volleyball) over at least the past 4 years, trained 2–3 times per week, and 25% of the subjects did additional upper-body strength training. Groups were matched for 5-m sprint, selected as measure for starting

speed, and countermovement jump with arm swing (CMJa), selected as measure for jumping performance. Subjects were instructed to maintain their regular activities during the study and 2 dropped-out because of illness or injury (respectively from Low and Control). Subjects also provided written informed consent before participating in the study. All procedures were in accordance with the ethical standards of the Helsinki declaration, and the study was approved by the ethical committee of the Ghent University Hospital (Belgium).

Procedures

Plyometric Training Program. The training program consisted of 2 training sessions per week (conducted on a wooden gymnasium floor) during a period of 8 weeks, with a rest period of at least 48 hours in between training sessions. Each training started with a general warm-up of 15' consisting of light running followed by dynamic stretching and accelerations. Each group was assigned different volumes and intensities of jumps, but training load and training load progression (i.e., 10% per week) were kept equal between groups. The first experimental group increased the training load by maintaining a mix of low- and high-intensity exercises and increasing the amount of contacts (Mix); the second group maintained the training volume and increased intensity (LowHi); and a third group only performed exercises from the lower end of the intensity spectrum and increased the training volume (Low) (Figure 2 and Table 2).

The volume of the PT is expressed as the amount of contacts during a training session (25). The intensity of the plyometric exercises was determined in 6 representative subjects by measuring the maximal ground reaction force (GRF; 500 Hz; AMTI, Watertown, MA, USA), minus body mass, during both the takeoff and landing phase (10). In addition, the generated impulse (GRF \times contact time) was determined as the sum of GRF that exceeded the subject's body mass (17). Recently it has been recommended to combine these 2 parameters to get a better insight into both the peak impact of the exercise (maximal GRF) and the jump as a whole (impulse) (15). Therefore, the plyometric exercises were first scaled to the exercise that elicited the lowest values for maximal GRF and likewise to the impulse. Thereafter, the intensity factor (IF) was determined as the average of these variables and organized into an intensity spectrum (Figure 3).

Performance Tests. Speed and agility were measured using an automatic timing system: Time started when passing the first gate and was registered after passing each next gate (Witty Gate Wireless Photocells; Microgate, Bolzano, Italy; accuracy 0.0004 seconds). A 10-m sprint with free start was used to evaluate the starting speed (time at 5 m) and general speed (time at 10 m). To

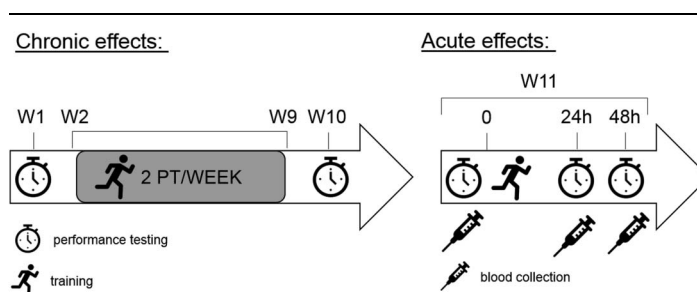


Figure 1. Experimental procedure.

Table 1
Description of subjects' characteristics before and after the training.

	Mix	LowHi	Low	Control
Age (y)	21.8 ± 2.1	21.3 ± 2.0	22.4 ± 1.5	22.5 ± 0.5
Height (cm)	180.6 ± 7.3	177.9 ± 3.5	184.0 ± 5.9	178.2 ± 4.9
Body mass (pre) (kg)	81.2 ± 8.4	76.1 ± 8.1	81.8 ± 11.3	78.4 ± 9.7
Body mass (post) (kg)	81.8 ± 9.5	77.2 ± 7.6	82.9 ± 11.5	78.8 ± 10.8

measure agility, a 5 × 10-m shuttle run (5 × 10 m) was executed, in which subjects had to run 5 times 10 m as fast as possible. The subjects were instructed to accelerate maximally and cross the line with 1 foot while turning 180°. Tests were preceded with the same warm-up as the PT sessions and were conducted in the same order as they appear in the text, separated with a resting interval of 2'.

Jumping performance was assessed from 3 vertical (SJ, CMJ, and CMJa) and 1 horizontal (standing broad jump [SBJ]) oriented jumps. For the SJ, subjects were instructed to hold the hands in the hips and maintain a 90° knee flexion for 3 seconds before takeoff. During the CMJ, subjects still had to hold their hands in the hips but could freely choose the desired countermovement depth for takeoff. The only instruction accompanying the CMJa was to jump as high as possible. Jumping height was measured based on the subject's flight time (Optojump; Microgate). The SBJ was performed on a mat from which jumping distance could be determined to the closest cm. Subjects were instructed to jump as far forward as possible and had to land on both feet and hold this position.

Acute Effects of Plyometric Training on Performance and Blood Parameters. The week after the post-test, all experimental groups (Mix, LowHi, Low) repeated their final training session to quantify the acute load of a single PT of respectively mixed, high, and low intensity (Table 3). Therefore, the previously described performance tests were executed before and 24 and 48 hours after the training. To investigate the inflammatory response, CK and LDH levels were determined from a venous blood sample by means of a *ultraviolet* photometric method (Cobas C; Roche, Basel, Switzerland). The creatine kinase level is determined from the measured rate of nicotinamide adenine dinucleotide phosphate formation, which is directly proportional to the CK activity. Lactate dehydrogenase activity is calculated from the increase in absorbance

of nicotinamide adenine dinucleotide, of which the formation reflects the catalytic activity of LDH. Blood samples were taken from an antecubital arm vein with subject in a seated position.

Data Analysis. All subjects were given 2 attempts on each performance test of which the best one was retained for analysis with the exception of the 5 × 10-m shuttle run, which was only performed once if executed correctly. To evaluate the chronic effect of the PT program, the postmeasurements on the performance tests were expressed in relation to the pretraining program measurements using the following equation: % change = (post-measurement – premeasurement) × premeasurement⁻¹ × 100. The acute load of a single training session was assessed accordingly by expressing the postmeasurements of the performance and blood parameters to the pretraining measurement. For the purpose of clarification: the running times were scaled as such that a faster running time on the postmeasurement was reflected by a positive relative improvement.

Statistical Analyses

Statistical analysis was executed using SPSS (22.0), and *p* values <0.05 were considered statistically significant. First, the data set was thoroughly analyzed for outliers by means of *SD* from the mean ($\bar{X} \pm 2 SD$) and median absolute deviation ($MAD = b \times M_i \times (|X_i - M_i(X_i)|)$) with correction factor 2.5 (18). Descriptive statistics were calculated and displayed as mean ± *SD*. Repeated-measures analysis of variance determined significant changes in both chronic (i.e., as a result of the training program) and acute (i.e., 24 and 48 hours after a PT) performance. Post hoc, groups were analyzed 2 by 2 to determine which groups showed different training adaptations or performance alterations. To include a maximal of observations, all variables were examined separately. Cohen's *d* ESs were calculated for significant interactions and were evaluated as small (0.2), medium (0.5), large (0.8), and very large (1.3) (28).

Results

Chronic Performance Effects

No interaction effect (IE) was found for the 5-m (*p* = 0.776), 10-m (*p* = 0.580), 5 × 10-m (*p* = 0.237), and SJ (*p* = 0.114)

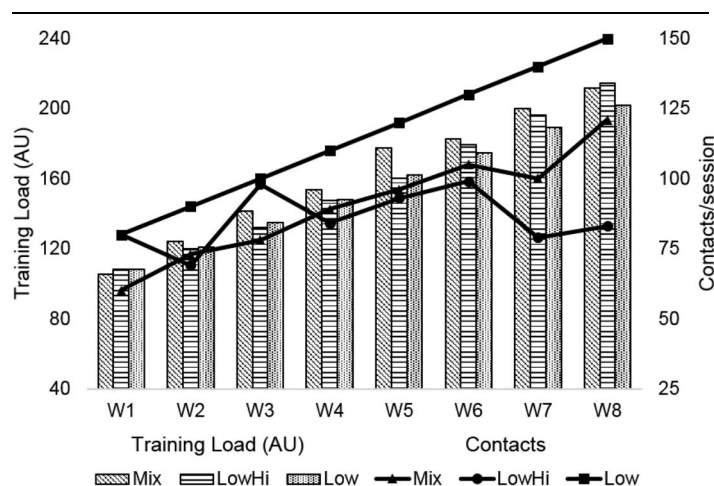


Figure 2. Graphical representation of the progressive overload including the amounts of contacts/session and the training load (AU) for the experimental groups.

Table 2
Description of plyometric exercises, intensity factor (IF), and group.

Exercise	Description	Verbal instruction	IF	Group
Skipping	Speed ladder skipping	Short contact time	1.00	Mix, LowHi, and Low
Double leg hops	Low hurdles (15 cm) hops	Short contact time, jumping height sufficient to take hurdles	1.49	Mix, LowHi, and Low
Running jumps	Accent horizontal displacement	Submaximal intensity	1.37	Mix, LowHi, and Low
Jumping lunges	Lunge—scissor jump—lunge	Jumping height sufficient to switch legs	1.7	Mix, LowHi, and Low
Depth jumps (50 cm)	Step from box + maximal vertical jump	Step from box and reach maximal jumping height	3.23	Mix and LowHi
Consecutive countermovement jumps	Three successive countermovement jumps without rest	Repeat 3 jumps (maximal height) without rest	1.49	Mix and LowHi
Standing broad jumps	Accent horizontal displacement with arm swing	Jump as far as possible	3.9	Mix and LowHi
Depth drops (50 cm)	Step from box + stand still	Step from box and make sure knees do not pass feet during landing	2.17	Mix and LowHi

performance, indicating that the change in performance did not differ between the groups. However, when the training effects were examined within each group independently, some improvements were found: 5×10 -m test improved for the LowHi ($+3.4 \pm 2.9\%$ [-0.668 to -0.202 seconds], $p = 0.002$, $ES = -0.61$) and the control group ($+2.0 \pm 2.1\%$ [-0.459 to -0.028 seconds], $p = 0.032$, $ES = -0.88$), and SJ performance improved for the Mix, LowHi, and Low plyometric group (respectively, $+7.0 \pm 9.5\%$ [0.2 – 4.1 cm], $p = 0.038$, $ES = 0.34$; $+11.6 \pm 7.9\%$ [2.3 – 5.0 cm], $p = 0.001$, $ES = 0.74$; and $+5.4 \pm 5.7\%$ [0.3 – 2.8 cm], $p = 0.018$, $ES = 0.30$) (Figure 4A–D).

The results of the CMJ showed a significant difference between the groups (IE: $p = 0.002$). Post hoc analysis indicated that the experimental groups significantly improved compared with the control group (Mix: $p = 0.004$; LowHi: $p = 0.001$, and Low: $p = 0.042$). Countermovement jump improved for the Mix and LowHi plyometric group (respectively, $+6.1 \pm 7.4\%$ [0.4 – 3.5 cm], $p = 0.017$, $ES = 0.33$ and $+9.8 \pm 8.5\%$ [1.9 – 4.9 cm], $p = 0.001$, $ES = 0.66$) (Figure 4E).

An IE was found for the CMJa, indicating a different evolution between the groups (IE: $p = 0.012$). The improvement in the Mix ($p = 0.021$), LowHi ($p = 0.002$), and Low ($p = 0.006$) groups was significantly higher compared with the control group. Countermovement jump with arm swing improved for the LowHi ($+7.1 \pm 8.5\%$ [0.7 – 5.0 cm], $p = 0.015$, $ES = 0.47$) and decreased in the control group ($-3.5 \pm 2.9\%$ [-3.1 to -0.4 cm], $p = 0.016$, $ES = -0.28$) (Figure 4F).

The results of the SBJ showed a significant difference between the groups (IE: $p = 0.020$). Post hoc analysis indicated a larger improvement of the Mix ($p = 0.018$), LowHi ($p = 0.001$), and Low ($p = 0.034$) compared with the control group. Standing broad jump improved for the Mix, LowHi, and Low plyometric group (respectively, $+9.0 \pm 10.4\%$ [5 – 29 cm], $p = 0.009$, $ES = 0.54$; $+7.3 \pm 4.9\%$ [10 – 22 cm], $p = 0.001$, $ES = 0.81$; and $+3.2$

$\pm 5.3\%$ [1 – 18 cm], $p = 0.031$, $ES = 0.48$) (Figure 4G). A detailed overview of the chronic results of the training program can be found in Supplemental Digital Content 1 (see Appendix 1, <http://links.lww.com/JSCR/A139>).

Acute Effects

No IE was found for performance and inflammation markers 24 hours after the training (5 m [$p = 0.285$], 10 m [$p = 0.290$], 5×10 m [$p = 0.971$], SJ [$p = 0.115$], CMJa [$p = 0.408$], SBJ [$p = 0.900$], CK [$p = 0.869$], and LDH [$p = 0.077$]) or 48 hours after the training (5 m [$p = 0.872$], 10 m [$p = 0.239$], 5×10 m [$p = 0.627$], SJ [$p = 0.656$], CMJ [$p = 0.062$], CMJa [$p = 0.269$], SBJ [$p = 0.187$], CK [$p = 0.942$], and LDH [$p = 0.405$]), indicating that the change did not differ between the experimental groups except for CMJ 24 hours after the training ($p = 0.030$) (Figure 5).

However, data analysis of the independent groups showed that SJ decreased 24 hours after a PT of high intensity (group LowHi) ($-3.9 \pm 3.8\%$ [-2.4 to -0.5 cm], $p = 0.005$, $ES = -0.04$) but did not change 24 or 48 hours after the mixed- (group Mix) or low-intensity (group Low) session. Countermovement jump decreased 24 and 48 hours after a PT of high intensity (respectively, $-4.3 \pm 4.8\%$, $p = 0.011$ [-3.0 to -0.5 cm], $ES = -0.04$ and $-3.4 \pm 4.1\%$ [-2.5 to -0.3 cm], $p = 0.017$, $ES = -0.04$) but did not change 24 or 48 hours after the mixed- or low-intensity session. An IE was found at 24 hours between the high- and both mixed- and low-intensity training (respectively, $p = 0.033$ and $p = 0.030$) and at 48 hours between the high and mixed session ($p = 0.029$) (Figure 5D, E).

Creatine kinase increased 24 hours after a high and low PT (respectively, $+76.9 \pm 67.1\%$, $p = 0.012$ [29 – 188 U·L $^{-1}$], $ES = 0.51$ and $+62.4 \pm 68.1\%$ [7 – 167 U·L $^{-1}$], $p = 0.018$, $ES = 0.41$) and 48 hours after the mixed, high, and low session (respectively, $+84.0 \pm 98.7\%$ [25 – 175 U·L $^{-1}$], $p = 0.014$, $ES = 0.40$;

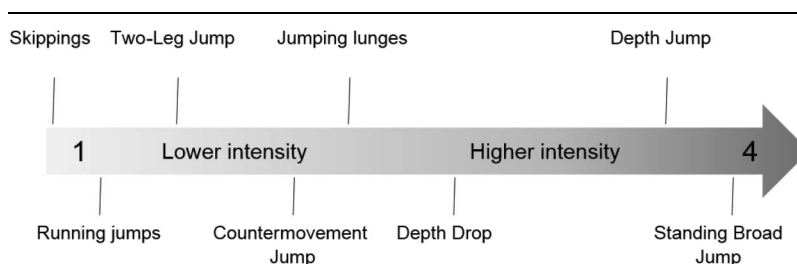


Figure 3. Relative intensity spectrum of plyometric exercises based on force plate measurements.

Table 3
Training characteristics to assess the acute effect of a plyometric training at mixed (Mix), high (LowHi), and low (Low) intensity.

	Mix	LowHi	Low
Contacts (<i>n</i>)	121	83	150
Intensity factor	1.95	2.7	1.39
Training load (AU)	212	214	202

+69.1 ± 68.1% [16–180 U·L⁻¹], $p = 0.023$, ES = 0.47 and +42.5 ± 40.5% [20–148 U·L⁻¹], $p = 0.017$, ES = 0.35). Lactate dehydrogenase increased 24 and 48 hours after a PT of high intensity (respectively, +13.7 ± 17.7% [3–32 U·L⁻¹], $p = 0.021$, ES = 0.12 and +13.3 ± 17.6% [3–31 U·L⁻¹], $p = 0.022$, ES = 0.11) but did not change 24 or 48 hours after the mixed- or low-intensity session. Lactate dehydrogenase increase was higher after the high PT compared with the mixed PT ($p = 0.037$) (Figure 5H, I). A detailed overview of the acute results of a single training session can be found in Supplemental Digital Content 2 (see Appendix 2, <http://links.lww.com/JSCR/A140>).

Discussion

This study is the first to compare PT programs with an equal training load progression (i.e., overload principle) but with a different contribution of volume and intensity. Generally, it was found that all PT programs had a positive impact on jumping performance and, to a lesser extent, agility, but did not affect sprint performance. However, no major differences could be established between the various PT programs. Importantly, the acute load of a high-intensity PT was found to induce a possible detrimental effect on jumping performance and more pronounced muscle damage (i.e., higher increase in CK and LDH) up to 48 hours after the training where this was not the case for sessions of mixed or low intensity consisting of the same training load.

Of all performance parameters, jumping performance was the variable affected most by the PT program. This comes as no surprise because previous studies generally report a positive effect of PT on vertical jumping performance, ranging from -0.4 to +10.4 cm (30). These results are in line with the progressions that the PT groups made during this study (+2.5 ± 2.4 cm, +2.3 ± 2.6 cm, and +2.0 ± 3.1 cm for, respectively, SJ, CMJ, and CMJa). Although both vertical and horizontal components were present in all training programs, PT did not affect sprint performance. These results are in accordance with the meta-analyses of de Villarreal (29,30), which show that the beneficial effect of PT is generally lower for sprint performance compared with jumping performance. This can be attributed to the training principle of specificity, which states that the mode and intensity of a training stimulus are determinative and specific in terms of exercise adaptations (13,27). The practical applicability of this principle is shown in the study by Markovic, where the group that received specific sprint training improved their performance to a greater extent than subjects receiving PT (21). Agility, as measured by the 5 × 10-m shuttle run, improved for the LowHi group. The fact that agility but not speed improved might be explained by the idea that PT mainly focuses on the properties of the stretch-shortening cycle that contributes to an efficient transition from eccentric to concentric muscle action, which is less pronounced in a straight-line sprint movement compared with a sprint with changes in direction (1).

The main finding of this study (i.e., that plyometric programs with a similar advancement in training load but a different progression in volume and intensity did not result in different performance improvements) should be considered in light of the mechanisms underpinning jump performance, i.e., force output during the concentric phase, timing and amount of stored elastic energy release, and energy balance. These determinants can be influenced by various forms of training, such as resistance training and PT, especially in inexperienced jumpers (3). It has been shown in the past that PT can increase agonist muscle preactivity and eccentric phase muscle activity, which will influence force output during the concentric phase and timing for release of elastic energy from the tendon (23). The training state of the subjects, considering our subjects had no experience with PT nor did they train more than 2–3 times per week in other sports, will most probably influence this relationship. It can be expected that in individuals unaccustomed to PT and resistance training, concentric muscle activity (which will impact concentric force output) is also enhanced after a plyometric program. Future research should examine the effect of initial strength levels and training status on performance adaptations following different training protocols. It has been suggested that weaker athletes should first increase their basic strength to maximize the training outcome of power-type (e.g., plyometrics) training sessions (27). The combination of strength and PT, also referred to as complex training, is often used to optimize the efficiency of the training program (12). It is possible that the training programs in this study exert a differentiated effect on the determinants of jump performance, e.g., with 1 program having a more pronounced effect on stored elastic energy and another having a stronger effect on the eccentric phase muscle activity. However, the different effects of the programs could be offset when they are combined within a performance measurement such as jumping and sprinting.

When we take a closer look at the experimental groups separately, a larger amount of performance variables improved from pretest to posttest for the Mix (4/7) and LowHi (5/7) group compared with the Low group (2/7). Although all groups experienced the same amount of TL, a certain level of intensity seems desirable to increase the likelihood of performance enhancement in, mainly, jumping performance. Following the fitness-fatigue model, an acute performance decrease is often observed the days after a training stimulus. It was observed that a PT of high intensity is more likely to cause a performance decrease compared with training sessions of low or mixed intensity, even if training load is equal. This is of importance regarding the training planning close to competition when a performance decrease should be avoided.

The novelty of this study can be found in the attempt to uncover the specific dose-response relationship by matching different periodization protocols (Mix, LowHi, and Low) for training load. Considering the fact that training outcome is a consequence of the imposed training load, both volume and intensity of the plyometric exercises should clearly be described (16). However, recently, a high-quality review article showed that 42% of the studies do not report plyometric intensity, presumably because of methodological difficulties, making it difficult to attribute performance adaptation to a specific program variable (i.e., volume, intensity, or training load) (24). It should be noted that up to the present day, no consensus exists regarding the best quantification method for plyometric exercises. Different quantification methods (e.g., electromyography or GRFs) provide us with a different ranking among plyometric exercises (11,31) and will influence

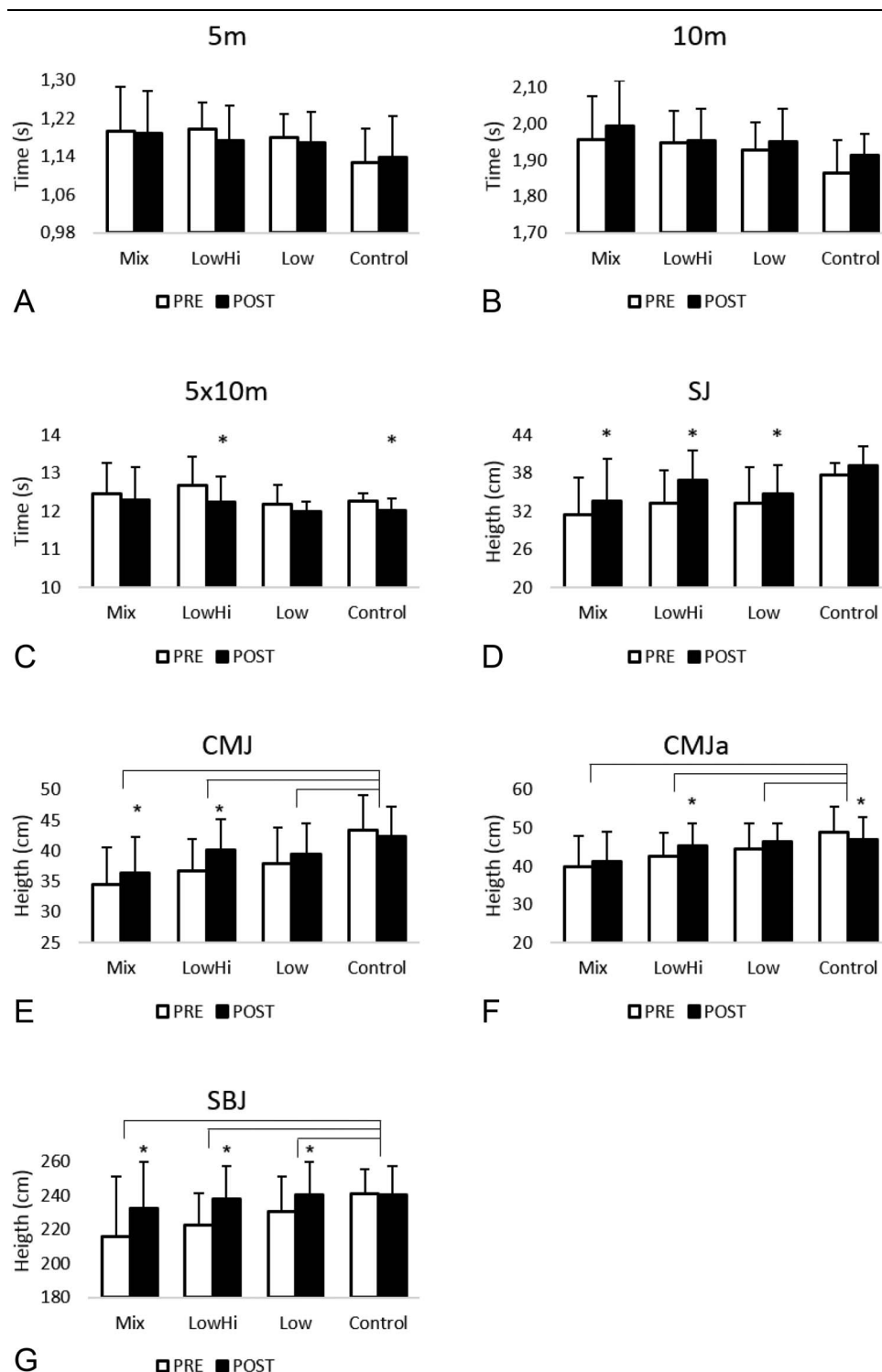


Figure 4. Chronic performance effects after 8 weeks of PT on 5-m sprint (5 m); 10-m sprint (10 m); shuttle run (5 × 10 m); squat jump (SJ); countermovement jump (CMJ); countermovement jump with arm swing (CMJa), and standing broad jump (SBJ). *Significantly different from pre-test ($p < 0.05$), \square Interaction effect ($p < 0.05$). PT = plyometric training.

the relationship between exercise intensity and performance adaptation. In addition, we also tried to clarify other key elements that are often neglected in studies assessing the effects of PT, such as incorporation of a control group, clear exercise description, surface type, number of jumps, progressive overload (characterization), and training status.

Limitations of the Study

It should be noted that the IF for the different exercises was determined by averaging the peak GRF and jumping impulse of 6 representative subjects. Future research might consider to further individualize the dose-response relationship by tailoring the

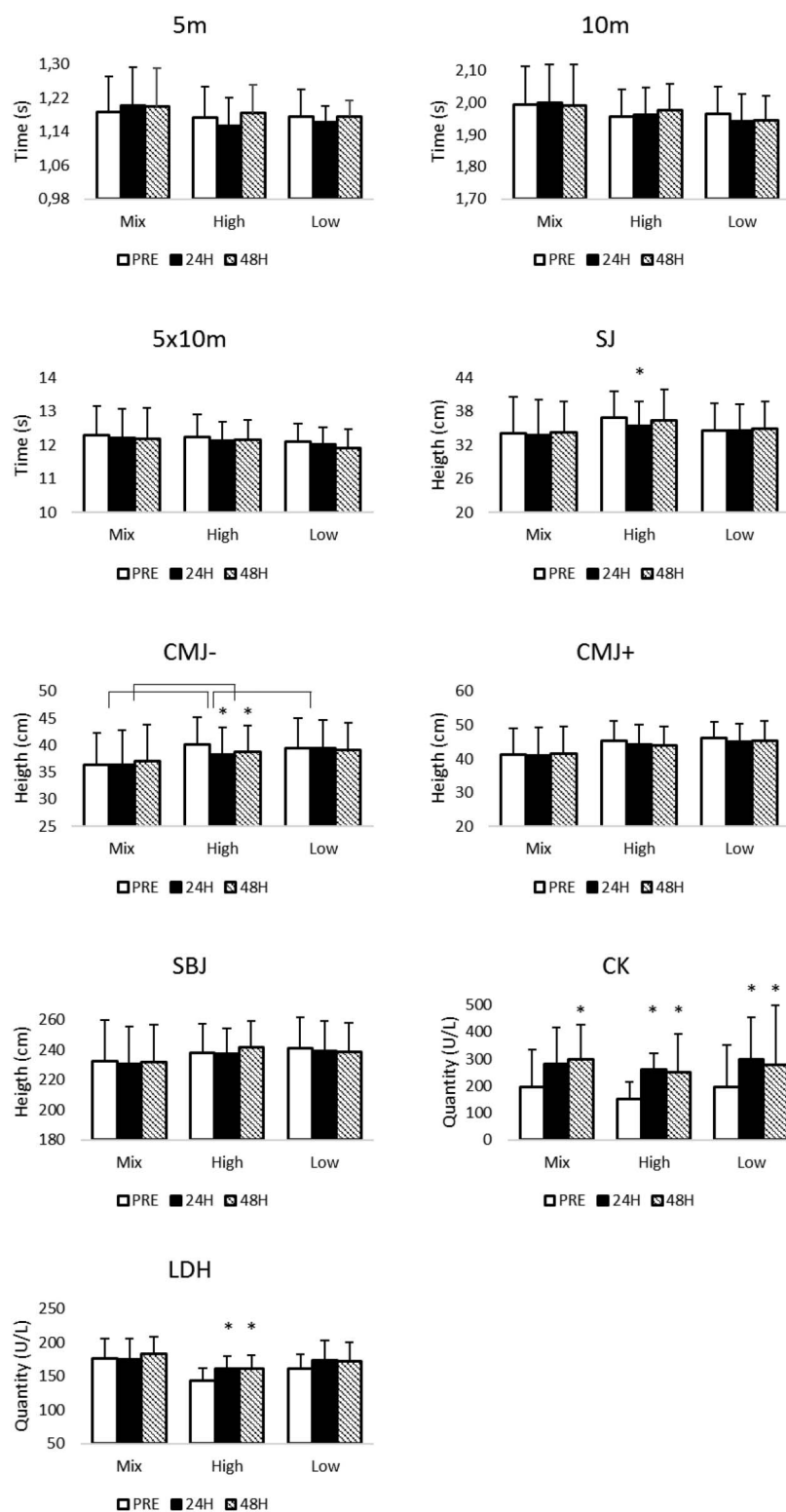


Figure 5. Acute effects after a PT of mixed (Mix), high (High), and low (Low) intensity on 5-m sprint (5 m); 10-m sprint (10 m); shuttle run (5 × 10 m); squat jump (SJ); countermovement jump (CMJ); countermovement jump with arm swing (CMJa); standing broad jump (SBJ); creatine kinase (CK), and lactate dehydrogenase (LDH) activity. *Significantly different from pre-test ($p < 0.05$), □ Interaction effect ($p < 0.05$). PT = plyometric training.

number of jumps with an individually determined IF. In this context, it was shown that verbal cues might strongly influence the specific kinematic profile of the plyometric exercises,

emphasizing the importance of the jumping technique in determining the overall training load (19). In addition, we did not include a control group when we investigated the acute impact of

the training sessions. However, several studies showed a good reliability and stability of both the performance and biochemical markers over a short period of time (6,8,26). Furthermore, both the stability and the reproducibility of the biochemical measurements were confirmed by the laboratory (Anacura, Belgium).

Practical Applications

The results of this study show that when training load (volume \times intensity \times frequency) is matched, different progression models of PT (i.e., increasing the volume, the intensity, or both) provide similar chronic performance benefits in recreational team sport athletes. However, a PT of high intensity has a larger acute impact on performance the days after the training compared with sessions at mixed or low intensity. Therefore, when close to competition, it might be more appropriate to plan a PT of low intensity with many contacts instead of a PT of high intensity and few contacts to minimize acute performance decline and still provide a sufficient stimulus to maintain and improve performance. These findings can be of particular importance in the training periodization for team sports where a weekly succession of competition is present.

Acknowledgments

This research is executed without additional research funding support. The results of this study do not constitute endorsement of the product by the authors or the NSCA. The authors have no conflicts of interest to disclose.

References

- Asadi A, Arazi H, Young WB, Saez de Villarreal E. The effects of plyometric training on change-of-direction ability: A meta-analysis. *Int J Sports Physiol Perform* 11: 563–573, 2016.
- Asmussen E, Bonde-Petersen F. Storage of elastic energy in skeletal muscles in man. *Acta Physiol Scand* 91: 385–392, 1974.
- Bobbett MF. Drop jumping as a training method for jumping ability. *Sports Med* 9: 7–22, 1990.
- Booth MA, Orr R. Effects of plyometric training on sports performance. *Strength Cond J* 38: 30–37, 2016.
- Cavagna GA, Dusman B, Margaria R. Positive work done by a previously stretched muscle. *J Appl Physiol* 24: 21–32, 1968.
- Chatzinikolaou A, Fatouros IG, Gourgoulis V, et al. Time course of changes in performance and inflammatory responses after acute plyometric exercise. *J Strength Cond Res* 24: 1389–1398, 2010.
- Chmielewski TL, Myer GD, Kauffman D, Tillman SM. Plyometric exercise in the rehabilitation of athletes: Physiological responses and clinical application. *J Orthop Sports Phys Ther* 36: 308–319, 2006.
- Darrall-Jones JD, Jones B, Roe G, Till K. Reliability and usefulness of linear sprint testing in adolescent rugby union and league players. *J Strength Cond Res* 30: 1359–1364, 2016.
- Davies G, Riemann BL, Manske R. Current concepts of plyometric exercise. *Int J Sports Phys Ther* 10: 760–786, 2015.
- Ebben WP, Fauth ML, Garceau LR, Petushek EJ. Kinetic quantification of plyometric exercise intensity. *J Strength Cond Res* 25: 3288–3298, 2011.
- Ebben WP, Simenz C, Jensen RL. Evaluation of plyometric intensity using electromyography. *J Strength Cond Res* 22: 861–868, 2008.
- Ebben WP, Watts PB. A review of combined weight training and plyometric training modes: Complex training. *Strength Cond* 20: 18–27, 1998.
- Foster C, Hector LL, Welsh R, et al. Effects of specific versus cross-training on running performance. *Eur J Appl Physiol Occup Physiol* 70: 367–372, 1995.
- Hill J, Leiszler M. Review and role of plyometrics and core rehabilitation in competitive sport. *Curr Sports Med Rep* 10: 345–351, 2011.
- Jarvis MM, Graham-Smith P, Comfort P. A methodological approach to quantifying plyometric intensity. *J Strength Cond Res* 30: 2522–2532, 2016.
- Jaspers A, Brink MS, Probst SGM, Frencken WGP, Helsen WF. Relationships between training load indicators and training outcomes in professional soccer. *Sport Med* 47: 533–544, 2017.
- Jensen R, Flanagan E, Jensen N, Ebben W. Kinetic responses during landings of plyometric exercises. In: *Proceedings of the XXVI Congress of the International Society of Biomechanics in Sports*. Kwon Y-H, Shim J, Shim JK, and Shin I-S, eds. International Society of Biomechanics, 2008.
- Leys C, Ley C, Klein O, Bernard P, Licata L. Detecting outliers: Do not use standard deviation around the mean, use absolute deviation around the median. *J Exp Soc Psychol* 49: 764–766, 2013.
- Louder T, Bressel M, Bressel E. The kinetic specificity of plyometric training: Verbal cues revisited. *J Hum Kinet* 49: 201–208, 2015.
- Markovic G. Does plyometric training improve vertical jump height? A meta-analytical review. *Br J Sports Med* 41: 349–355, 2007.
- Markovic G, Jukic I, Milanovic D, Metikos D. Effects of sprint and plyometric training on muscle function and athletic performance. *J Strength Cond Res* 21: 543–549, 2007.
- Markovic G, Mikulic P. Neuro-musculoskeletal and performance adaptations to lower-extremity plyometric training. *Sports Med* 40: 859–895, 2010.
- McBride JM, McCauley GO, Cormie P. Influence of preactivity and eccentric muscle activity on concentric performance during vertical jumping. *J Strength Cond Res* 22: 750–757, 2008.
- Ramirez-Campillo R, Alvarez C, Garcia-Hermoso A, et al. Methodological characteristics and future directions for plyometric jump training research: A scoping review. *Sport Med* 48: 1059–1081, 2018.
- Ramirez-Campillo R, Andrade DC, Izquierdo M. Effects of plyometric training volume and training surface on explosive strength. *J Strength Cond Res* 27: 2714–2722, 2013.
- Slinde F, Suber C, Surer L, Edwén CE, Svantesson U. Test-retest reliability of three different countermovement jumping tests. *J Strength Cond Res* 22: 640–644, 2008.
- Suchomel TJ, Nimphius S, Bellon CR, Stone MH. The importance of muscular strength: Training considerations. *Sports Med* 48: 765–785, 2018.
- Sullivan GM, Feinn R. Using effect size—Or why the P value is not enough. *J Grad Med Educ* 4: 279–282, 2012.
- Saez de Villarreal E, Requena B, Cronin JB. The effects of plyometric training on sprint performance: A meta-analysis. *J Strength Cond Res* 26: 575–584, 2012.
- de Villarreal ES, Kellis E, Kraemer WJ, Izquierdo M. Determining variables of plyometric training for improving vertical jump height performance: A meta-analysis. *J Strength Cond Res* 23: 495–506, 2009.
- Wallace BJ, Kernozek TW, White JM, et al. Quantification of vertical ground reaction forces of popular bilateral plyometric exercises. *J Strength Cond Res* 24: 207–212, 2010.
- Wilson GJ, Newton RU, Murphy AJ, Humphries BJ. The optimal training load for the development of dynamic athletic performance. *Med Sci Sports Exerc* 25: 1279–1286, 1993.